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Critical Literature Review

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What are the barriers to establishing effective wastewater management in Antarctica?

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Abstract:

Antarctica is often presented as earth's 'last untouched wilderness', however human induced impacts have been progressively transforming aspects of the environment since our arrival on the continent. Wastewater discharge from research stations is a significant vector of non-native microorganisms, high nutrients loads and a range of contaminants, and has been shown adversely affect the receiving environment in a variety of ways. Effective treatment technology now exists for cold environments and implementing wastewater treatment at all research stations would help reduce the potential suite of effects. Despite this, the management of wastewater in Antarctica is varied, with some stations still employing rudimentary treatment facilities or disposing raw sewage to the environment. In this review, the barriers to establishing effective wastewater management in Antarctica have been explored. The literature suggests that the environmental values of each country, the logistical/financial challenges of installing and operating treatment stations, and an outdated environmental protocol are the primary barriers to effective treatment systems being installed at all stations. It is likely that further advanced treatment plants will be installed at some stations in the future, given a growing awareness of the impacts of untreated wastewater in Antarctica. However, this is likely to be the result a country's values rather than regulatory requirements.

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1. INTRODUCTION

In a world with over 7 billion people, it is rare to find areas that are relatively unaffected by human influence. Due to its remoteness and harsh conditions deterring large scale human inhabitation Antarctica has, for the most part, resisted colonisation and is often regarded as earth's 'last untouched wilderness'. However, from the first heroic era of Antarctic exploration onwards (1900s), human activity has grown significantly. At present around 40,000 tourists visit the continent annually (IAATO, 2016), and active research stations in Antarctica can accommodate a peak population of over 4500 during summer (COMNAP, 2016b). According to COMNAP's (2016b) statistics there are approximately 40 active year round and 39 summer scientific research stations, operated by 28 countries who are party to the Antarctic Treaty.

Human induced impacts are inevitable with increased numbers visiting and the variation of activities they undertake in the Antarctic (Bargagli, 2008). In order to promote adequate sanitation, reduce offensive odours and minimise environmental effects, wastewater disposal or removal is a practical necessity for research stations in Antarctica (Smith & Riddle, 2009). Treatment practices have come a long way in the last decade, for example, an advanced wastewater treatment plant will soon be installed at Australia's Davis Station which has remote access features and the ability to produce potable water as an end product (Zhang, 2016).

Regulations for wastewater have been established under the Protocol on Environmental Protection to the Antarctic Treaty (1991) and guidance on best practice for monitoring discharges is available from COMNAP (COMNAP, 2005). Despite regulations and effective treatment technology existing for the Antarctic climate, only 63% of permanent stations and 31% of summer stations have reported undertaking some form of treatment (Gröndahl *et al*., 2009). Currently each research station has developed their own method of undertaking wastewater disposal. This can vary according to the station's population, location on the continent, and motivations for establishing effective treatment, such as resembling what is undertaken in the home country (Connor, 2008; Gröndahl *et al*., 2009; Tarasenko & Gilbert, 2009).

1.1 AIMS OF THIS REVIEW

The aim of this review is to evaluate the contemporary information on wastewater treatment practices in Antarctica and key environmental effects. In conjunction with this, barriers to establishing consistent, effective wastewater treatment will be explored from a regulatory and logistical perspective.

Recent overarching reviews of wastewater treatment in Antarctica have been undertaken by Stark *et al*. (2016a, 2015). More targeted reviews in the field include Gröndahl *et al*. (2009) who reported the findings of a 2005 survey on research station practices, and presents the most recent data available that comprehensively compares each station. Smith and Riddle (2009) and Tin *et al.* (2009) have summarised wastewater disposal practices in the context of general environmental effects. Tarasenko (2009), a previous GCAS student, has discussed the technicalities of transferring wastewater treatment technologies to the Antarctic and has provided a summary of what was undertaken at each research station. Connor (2008) has summarised the trends in wastewater management in Antarctica and the current state of engineering knowledge for constructing effective treatment systems in cold environments.

2 TREATMENT PRACTICES

The term 'wastewater' is used in this review to describe both greywater and human sewage. Greywater is produced predominately by domestic sources such as showers, kitchens, laundry facilities, and in some cases can include light industrial waste, such as laboratories and workshops (Gröndahl *et al*., 2009; Stark *et al*., 2015). Greywater from a station often contains a variety of substances such as fats, oils and detergents (Gröndahl *et al*., 2009). The treatment of wastewater can involve multiple steps to remove or break down different substances. Primary treatment involves the separation of solids, usually via grating or screening and occasionally settlement. Secondary treatment involves aerobic and anaerobic biological treatment, reducing organic and inorganic substances. Tertiary treatment is considered the final physiochemical processing to remove macro substances and denature microorganisms and pathogens (Smith & Riddle, 2009). The final treated effluent is disposed of into the receiving environment nearby, or removed from Antarctica to be treated elsewhere (Gröndahl *et al*., 2009).

The degree of wastewater treatment and effectiveness between stations vary; some have secondary or tertiary treatment facilities with outfalls into the ocean, while others have no facilities and discharge raw sewage (Gröndahl *et al.*, 2009; Stark *et. al.*, 2016a). Stations positioned on the coast generally have near-shore outfalls which discharge to the sea ice or intertidal zone (Smith & Riddle, 2009), while waste from inland field camps is often disposed of in ice-pits, subsurface ice wells lakes, or completely removed for treatment at the home country (Smith & Riddle, 2009). As shown in Figure 1, most research stations are located on the coast in bays or near sea ice, which can lead to localised environmental effects (Stark *et al.*, 2016b).

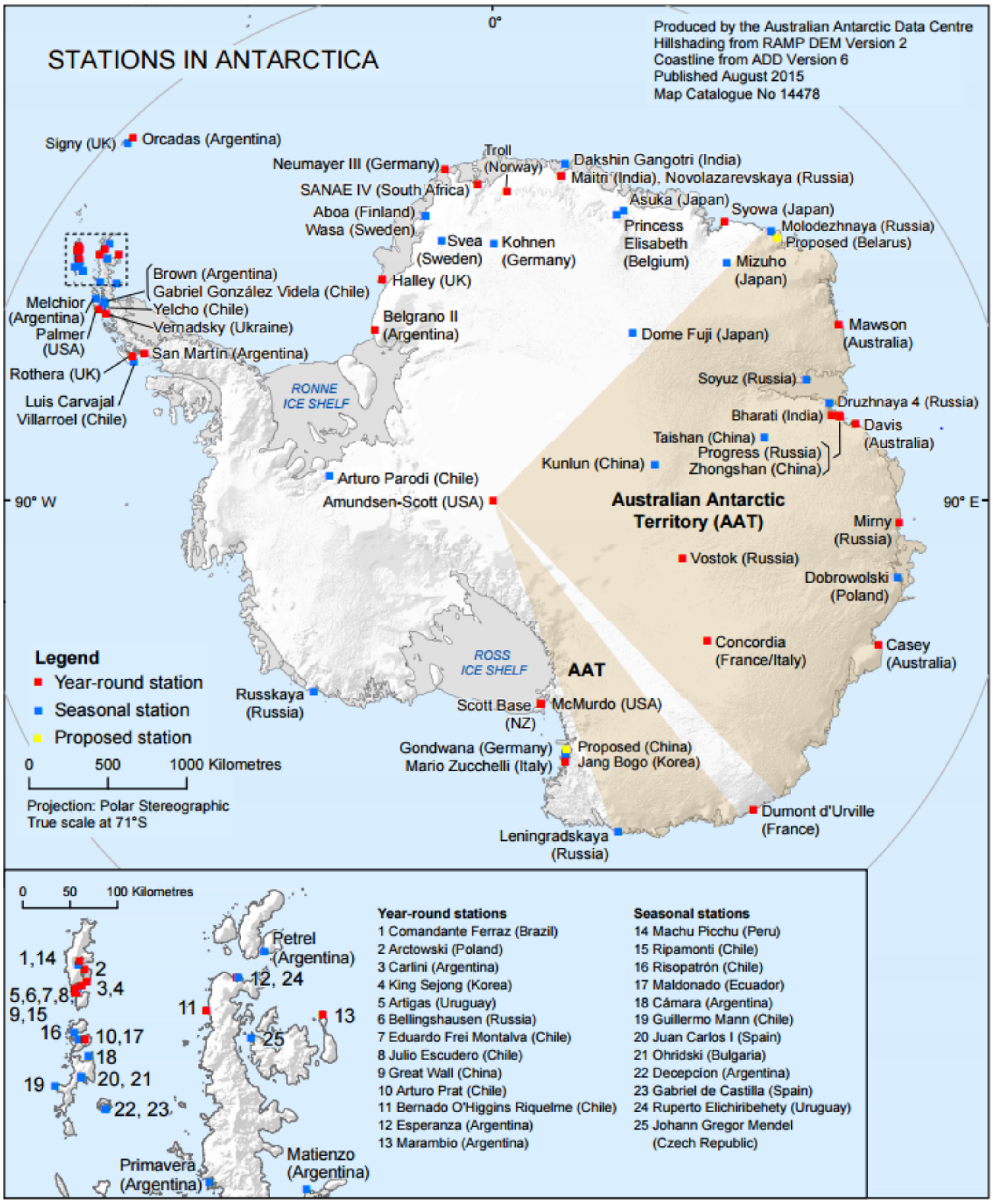

Figure 1: showing the locations of permanent, summer and proposed Research Stations in Antarctica (From Australian Antarctic Division, 2015)

2.1 LOGISTICAL CHALLENGES TO ESTABLISHING EFFECTIVE TREATMENT

The cost to establish and operate a treatment plant is a significant barrier to installing a new plant. Secondary treatment plants cost around $500,000 USD without factoring in installation costs (COMNAP, 2014), while equipment and installation can be as high as several million (Gröndahl *et al*., 2009). Treatment plants are also challenging to transport; generally parts are shipped in containers and reassembled in Antarctica (Tarasenko & Gilbert, 2009). Extreme conditions and long periods of darkness make construction challenging, as there are only around eight weeks in summer when outdoor construction work can occur (Heaton & Paterson, 2003; Tarasenko & Gilbert, 2009).

Because of the isolated environment, plants need to be well-designed to ideally be low-maintenance, robust and dependable (Connor, 2008). Station staff are usually assigned to multiple tasks, and there can be a high staff turnover, so personnel trained specifically for wastewater plant operations are rare, especially during winter (COMNAP, 2014; Connor, 2008; Tarasenko & Gilbert, 2009). Isolation makes the transport of spare parts time consuming, and plants may need built-in redundancy measures (such as holding tanks) to account for this (Connor, 2008; Tarasenko & Gilbert, 2009). Population numbers during winter can be 10% of the summer numbers, causing hydraulic loading rates to vary significantly, which can be a challenge when it comes to designing a plant (Connor, 2008). In addition, the cold means that systems often need to be heated in order for them to work optimally and prevent pipes from freezing (COMNAP, 2014; Tarasenko & Gilbert, 2009).

An ideal treatment plant would be modular and prefabricated enabling ease of transport, and able to be operated remotely (Connor, 2008). COMNAP (2014) have listed other key features for an ideal plant such as a compact design, provision to reuse treated water, ease of start-up for summer stations and the ability to operate under different loading parameters for summer/winter.

An effective system involving primary, secondary and tertiary processes is generally considered expensive and impractical for small stations (Aronson *et al*., 2011). Despite this, minimum treatment standards of secondary treatment and disinfection (e.g. UV treatment), is recommended in order to reduce contaminant loading and denature non-native microbes (Smith & Riddle, 2002).

3 ECOLOGICAL EFFECTS

Wastewater contamination can affect the receiving environment in a variety of ways depending on the method of discharge, level of treatment, and conditions at the disposal site (Aronson *et al*., 2011). The discharge can facilitate the introduction of pathogens and non-native microorganisms, and contain contaminants such as heavy metals, organic material and micro pollutants, which can all have a range of effects on communities and ecosystems in the vicinity of the disposal area. Antarctic species have slow growth and development rates and can live for long periods (Peck, 2002), and so variations to their environment can have long-lasting effects (Bargagli, 2008).

3.1 INTRODUCTION OF NON-NATIVE SPECIES

Smith and Riddle (2009) consider the introduction of non-native species from wastewater to be one of the most significant environmental impacts of any human activity in Antarctica. As deliberate introduction of species via any other mechanism is prohibited, wastewater discharge is now the primary vector for introduction (Smith & Riddle, 2009). Sewage in particular harbours human-associated bacteria (*Escherichia coli* in particular) which can be released into the marine environment if there is ineffective treatment (Power *et al*. 2016). These strains likely differ from those found in animals, and so pollution may be altering the genetic makeup of endemic microbes (Power *et al*., 2016), 'dumbing down' the uniqueness of Antarctic fauna (Aronson *et al*., 2011).

3.2 BENTHIC ECOSYSTEMS

Another significant effect from coastal outfalls is on surrounding benthos. Benthic ecosystems in Antarctica have high biodiversity values, and are more likely to be impacted by contaminants (Bargagli, 2008). Communities around highly polluted wastewater treatment outfalls can show shifts in community structure, including a decrease in abundance and increases in pollution tolerant species (Conlan *et al*., 2004, 2010; Bargagli, 2008). Pollution has also been shown to cause metabolic changes in species of Antarctic cod, where they exhibit an oxidative stress response (Rodriguez Jr *et al*., 2015), and Corbett (2014) reported histopathological changes in Antarctic cod in the vicinity of the Davis Station outfall.

3.3 EMERGING CONTAMINANTS

Technological advancement has enabled a wide range of different compounds to be manufactured and included in products that may be present in wastewater (Bolong *et al*., 2009). Contaminants that have been recently studied in Antarctica include personal care products and pharmaceuticals (referred to as PPCPs) which can include detergents, sunscreens, lotions, toothpaste and antibiotics (Emnet *et al*., 2015; Tin *et al*., 2009). While many of these compounds degrade quickly once in the receiving environment, constant discharge from wastewater facilities can enable a persistent presence and constant exposure for those organisms in the vicinity of the discharge (Emnet *et al*., 2015). Many (e.g. UV filters in sunscreens) are known to have endocrine disrupting properties, and others (e.g. types of paraben) have been shown to bioaccumulate in the tissue of Antarctic organisms (Emnet *et al*., 2015). Flame retardants or PBDEs discharged with wastewater have also been shown to bioaccumulate and persist in coastal environments (Hale *et al*., 2008). In addition to this, antibiotic resistance has been found in local microbes around wastewater treatment plants in Antarctica (Marti *et al*., 2013; Rabbiba *et al*., 2016)

Evaluating the prevalence of emerging contaminants in Antarctica is a relatively new field of research (Emnet *et al*., 2015). Not much is known about PPCPs in particular and their environmental effects. From a logistical perspective, the removal of emerging contaminants from wastewater often requires advanced treatments such as activated carbon, nanofiltration and reverse osmosis (Bolong *et al*., 2009). These practices can add complexity to the treatment process and would require the upgrade of existing treatment plants in Antarctica.

4 REGULATORY TOOLS

The Protocol on Environmental Protection to the Antarctic Treaty (referred to as "the Madrid Protocol" or "the protocol") was adopted in 1991 and was the result of synthesising a range of previously agreed environmental management measures and the growing international concern for human environmental degradation (Connor, 2008). So far, 37 countries have signed the protocol (COMNAP, 2016a). ANNEX III to the protocol sets out minimum standards for waste disposal and management. These measures are split depending on the sink for the waste (air, land, water or removal from Antarctica). The preferred method is removal from Antarctica, and the protocol states this should be undertaken to the 'maximum extent practicable'. Where this is not practical, the protocol specifies that wastewater should not, as far as practicable, be disposed of onto ice-free areas or into freshwater systems. If it is disposed of into the sea, the receiving environment conditions should favour initial dilution and rapid dispersal, and quantities generated by more than 30 people must be macerated. The by-products of sewage treatment processes may be disposed of into the sea provided there are no adverse environmental effects. ANNEX II to the Madrid Protocol does not allow the purposeful introduction of non-native species to Antarctica without a permit, and requires that a precautionary approach is taken to activities to prevent introduction of non-native species, parasites and diseases (Stark *et al*., 2016a).

4.1 EFFECTIVENESS OF THE MADRID PROTOCOL

Many research stations were established before the Madrid Protocol came into effect and would have factored logistics and accessibility rather than dispersal and rapid dilution of wastewater when selecting a site (Stark *et al*., 2016a). The result is that most are on ice free land, or in shallow bays with long sea ice duration, which are not conducive to rapid dispersal (see Figure 2) (Stark *et al*., 2016a). In addition, these environments often have unique species assemblages which increases the environmental risk (Stark *et al*., 2016a). Most research stations have not evaluated the impact of sewage pollution on the nearby environment (Aronson *et al*., 2011). While the Madrid Protocol spurred some countries to further their treatment practices, many do not go beyond the minimum requirements laid out in the Madrid Protocol, while other countries use their own treatment practices in their home country to set high standards for treatment (Connor, 2008).

Figure 2: "The Davis Station wastewater outfall when the sea ice is in" (From Stark *et al*., 2016a)

The emphasis in the Madrid Protocol on rapid dispersal and dilution alone are widely recognised as being insufficient to prevent environmental effects (Smith & Riddle, 2009; COMNAP, 2014). In particular, the protocol does not set specific limits on treated wastewater quality or on the level of treatment e.g. whether pathogens and microorganisms need to be denatured (Tarasenko & Gilbert 2009; COMNAP, 2014; Stark *et al*., 2016a; Rabbiba *et al*., 2016). With regard to emerging contaminants, the development of new compounds has now outpaced the development of limit setting across the world (Bolong *et al.,* 2009). The treaty has been considered inadequate to prevent large-scale contamination and a new regulatory tool may be required for this purpose (Bargagli, 2008).

ANNEX III of the Madrid Protocol states that monitoring of wastewater effects shall take place, however it is non-specific in what should be monitored (Smith & Riddle, 2009). Monitoring is not currently undertaken for all wastewater stations in Antarctica (Smith & Riddle, 2009; Aronson *et al*., 2011), and permanent monitoring of wastewater quality is not usually practical due to a lack of dedicated staff or facilities (Tarasenko & Gilbert, 2009). In particular, microbiological monitoring is identified as being necessary for assessing disease transfer to wildlife and non-native introductions of microorganisms (Stark *et al*., 2016a; Smith & Riddle, 2009). It has been suggested by Bargagli (2008) that large scale monitoring programmes should be introduced for the purpose of assessing the effects of contaminants on food-webs. They suggest that international agreements should be established with financial aid to enable wide-scale effects to be addressed.

Under Article 17 of the Madrid Protocol, all parties must report annually on the steps taken to implement the protocol. These reports can be a valuable source of information in checking who is currently adhering to the protocol, or if further treatment measures are planned (UNEP & ASOC, 2011). In a review by ASOC and UNEP on the Madrid Protocol implementation, it was found that between 2000 and 2010 approximately 50% of consultative treaty parties on any given year adhered to the Article 17 annual reporting requirements (where they report their implementation progress to all parties). As at 2010, at least 30% of parties had never reported (UNEP & ASOC, 2011). This adds to the general lack of current, public information on the wastewater treatment methods for many research stations (Tarasenko & Gilbert, 2009; Gröndahl *et al*., 2009; UNEP & ASOC, 2011). Another obstacle with the Antarctic Treaty and Madrid Protocol is that they rely on the commitments of governments to carry out the protocol; active enforcement of the measures does not occur as each country usually ratifies and enforce the protocol under their own domestic legislation (Aronson *et al*., 2011; Stark *et al*., 2015).

5 SUMMARY AND CONCLUSIONS

The design requirements for effective wastewater treatment in Antarctica are now well understood, and much can be learnt from countries who have already established treatment systems. Although this is the case, many countries still operate bases without any form of effective treatment. The literature indicates that the primary reason for a lack of treatment is values based, closely followed by the logistical and financial challenges of operating a treatment plant. A wastewater treatment plant can be a significant investment for a small scale research station, and it appears those who invest in effective treatment are likely to be investing money to align with practices undertaken in their own country, or to meet the minimum requirements of the Madrid Protocol. Despite this, the requirements of the Madrid Protocol are widely regarded as insufficient to prevent adverse environmental effects, such as the introduction of non-native microbial species, spread of antibiotic resistance and release of a range of contaminants. The countries who value environmental protection have generally taken treatment several steps beyond the minimum standards set out in the Madrid Protocol.

Most studies that have evaluated the effects of wastewater come from a small sample of stations such as McMurdo, Casey, Scott and Davis and have, for the most part, focussed on benthic organisms and microbes. While these papers provide useful information, more studies from other stations should be encouraged, given that most stations are situated in a unique environment. In particular, a co-ordinated, large-scale monitoring is needed for contaminants that are shown to persist or bioaccumulate in the environment (thus spanning a range of food webs), so that the full impact of these contaminants on ecosystems is understood.

Significant information gaps in the literature also exist on wastewater treatment practices at all stations. Although the survey undertaken by Gröndahl *et al*. (2009) in 2005 is still informative, the information presented is now outdated. Many parties do not submit their status reports under the Madrid Protocol and so it is difficult to assess the current level of wastewater treatment at all stations. Regular follow up surveys would be helpful in this regard, as they could prompt countries to share this information.

Given the evidence demonstrates that discharges of wastewater are having adverse effects on the environment, and that the Madrid Protocol is insufficient in mitigating this risk, the literature suggests that a precautionary approach to environmental management should be considered. Smith & Riddle (2009) have suggested a minimum of secondary treatment and a microorganism denaturing mechanism (such as UV), which seems like a logical option given the strong concerns around non-native microbe introduction. It is even challenging for modern wastewater facilities to remove the variety of contaminants that wastewater contains, therefore an updated precautionary regulatory tool that anticipates, rather than responds, to effects would be beneficial for the Antarctic environment. Regardless of the regulatory framework, it is likely that more countries will recognise the need for improved treatment in the future and practices will be updated to reflect this.

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